MULTIMEDIA UNIVERSITY

STUDENT ID NO

TABLE NO:

MULTIMEDIA UNIVERSITY

FINAL EXAMINATION

TRIMESTER 2, 2017/2018

TSN1101 – COMPUTER ARCHITECTURE AND ORGANIZATION
(All Sections /Groups)

2 MARCH 2018
9.00 a.m. - 11.00 a.m.
(2 Hours)

INSTRUCTIONS TO STUDENTS

1. This Question paper consists of 23 pages (excluding this page and the Appendix) with 2 Sections. Each Section contains 4 Questions.

2. Attempt a total of 5 Questions, with a maximum of 3 Questions from any 1 Section and the remaining 2 Questions from the other Section. Each Question carries 12 marks and the distribution of the marks for each subdivision is given. Maximum allotted marks are 60 marks.

3. Please write all your answers in the Question Paper itself in the space provided.

SECTION A

Question A1

a) Complete the following table by performing the appropriate conversions.

Decimal	Binary	Hexadecimal	(8 4 -2 -1) code	Gray code
67.875				

(4 marks)

Continued...

b) Identify the results of the arithmetic operation [(43 + 42) – 41] in the following number systems:
   i) Octal (Base 8)
   ii) Quinary (Base 5)
   Show all your calculations.

(2 marks)

Continued...

c) Assume the decimal numbers given are

$$X = -49 \text{ and } Y = -78$$

i) Represent the above decimal numbers in 8-bit two's complement binary representation.

ii) Perform [(X) − (Y)] with the numbers represented in 8-bit two's complement binary form.

(1+1=2 marks)

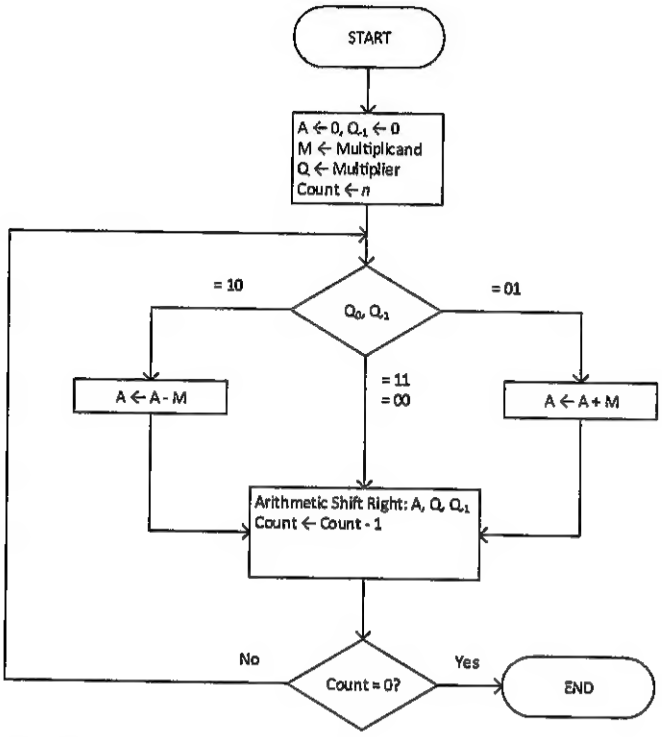
Continued...

d) Perform the multiplication of two 4-bit two's complement binary numbers given below. Use Booth's algorithm (flowchart is given below).

Multiplicand (M) = 1110_2 or -2_{10}

Multiplier (Q) = 0011_2 or 3_{10}

(4 marks)



M	A	Q	Q_{-1}		
					Initial values
					First cycle
					Second cycle
					Third cycle
					Fourth cycle

Continued...

Question A2

a) 'AND gate can be called a negative NOR gate'. Prove the validity of the statement by constructing the truth tables for two input AND gate and two input negative NOR gate.

(2 marks)

Continued...

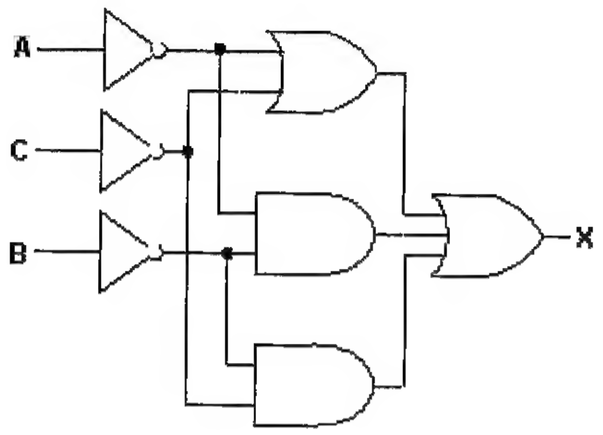
b)

i) Write the Boolean expression for the output X in the following logic diagram.

ii) Simplify the Boolean expression to the simplest form using rules of Boolean algebra.

iii) Write the truth table by using the simplified Boolean expression.

(2+2+2=6 marks)



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c) For the Boolean function, $F = (A\overline{B}) + (B\overline{C}) + (\overline{A}B\overline{C})$

(i) Construct the appropriate truth table, and
(ii) Find the standard SOP and standard POS expressions.

(2+2=4 marks)

Continued...

Question A3

a) Assume that a student has to go through three different assessments (Mid-term Test assessment, Lab assessment and final exam assessment) before obtaining the result for a subject. Assume that staff has marked 1 for the result of the assessment if he/she passes that assessment or 0, if he/she fails that assessment. The student has to get minimum of two 1's in the assessment results in order to pass the subject.

Three input signal lines indicate the results of assessments and the single output signal line indicate the final result of the subject. The output should be 1 if the student passes the subject and 0 if he/she fails.

i) Draw the truth table for the above problem indicating all possible combinations for the results of assessments and the corresponding final result of the subject.
ii) Minimize the expression into simplified Sum-of-Products (SOP) form.
iii) Construct a logic diagram using AND-OR gate network.

(3×2=6 marks)

Continued...

Continued...

b) Construct the truth table for the Half-Adder Circuit with two inputs (Augend (X), Addend (Y)) and two outputs (Carry Out (C_{out}), Sum (S)).

(2 marks)

Continued...

c) Implement the following Sum of Products Boolean expression, using an 8×1 multiplexer.

$$F = A'BC'D' + A'BCD' + A'BCD + AB'C'D + ABC'D' + ABC'D$$

Perform the following steps for the implementation:

i) Construct the truth table and evaluate the output, F as 0, 1, variable D or the complement of variable D.

ii) Draw the connection diagram using an 8×1 multiplexer.

(2+2=4 marks)

Continued...

Continued...

Question A4

a) A synchronous counter has three negative-edged triggered D flip-flops and three inputs X, Y and Z. Design the counter based on the sequence listed below:

001, 010, 100, 110, 111 and repeats

Undesired states go to don't care on the next clock pulse.

i) Complete the excitation table.

(3 marks)

ii) Simplify D_X, D_Y and D_Z and using K-maps.

(6 marks)

iii) Draw the synchronous counter.

(3 marks)

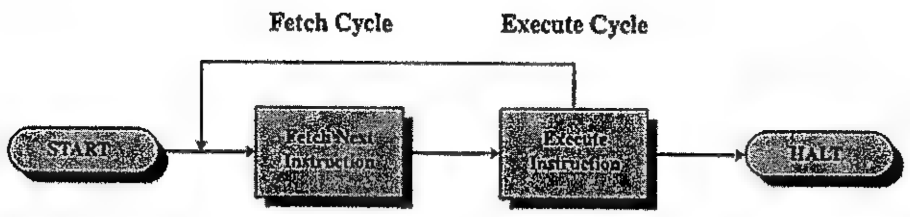
Continued...

Continued...

SECTION B

Question B1

a) The processing required for a single instruction is called an instruction cycle. A simplified three step cycle will include the fetch, execute and interrupt cycles. The basic instruction cycle is shown below:



List the actions taking place during the fetch cycle.

(4 marks)

b) The system interconnection that connects major computer components (processor, memory, I/O) is called a system bus. List and describe the THREE major modules of the system bus.

(3 marks)

Continued...

c) Many processor designs include a register, often known as the program status word or status bits register that contain status information. List four common status bits.

(2 marks)

d) Assume that a processor that employs a memory address register (MAR), a memory buffer register (MBR), a program counter (PC), and an instruction register (IR). During the fetch cycle, an instruction is read from memory. List the flow of data during this cycle in the correct order.

(3 marks)

Continued...

Question B2

a) Assume a three-stage pipeline (fetch, execute & write). Draw a timing diagram to show how many units are needed for four instructions.

(2 marks)

b) Assume that a processor employs a memory address register (MAR), a memory buffer register (MBR), a program counter (PC), and an instruction register (IR), supporting only one-address instructions. List the symbolic sequence of micro-operations for a fetch cycle.

(4 marks)

Continued...

c) Assume that Word 11 contains 22, Word 22 contains 33, Word 33 contains 44, and Word 44 contains 55. Given the memory values above and a one-address machine with an Accumulator (Register A), what values do the following instructions load into the Accumulator?

i)	LOAD IMMEDIATE 44	ii)	LOAD DIRECT 33
iii)	LOAD INDIRECT 22	iv)	LOAD IMMEDIATE 22
v)	LOAD DIRECT 11	v)	LOAD INDIRECT 22

(3 marks)

d) In processor pipelines, in order to overcome branch hazards, static branch prediction techniques can used. Name these static branch prediction techniques.

(3 marks)

Continued...

Question B3

a) Machine instructions operate on data (operands). What are the THREE general categories of operands?

(2 marks)

b) Given the following registers and a two-address machine, give your program to compute $Z = (W - X)/(Y + P \times Q)\ /\ (Y - X)$. Available instructions are given below:

a. Registers: A, B and C
b. Instructions: MOV R1,#DATA; MOV R1, R2; ADD R1, R2; SUB R1,R2; MUL R1,R2 and DIV R1,R2

Store the result in Register A. (Hint: Instruction format – opcode destination, source)

(3 marks)

Continued...

c) Suppose an 8-bit data word stored in memory is 01111001. Using the Hamming algorithm, determine what check bits would be stored in memory with the data word. Show how you got your answer.

(5 marks)

Bit Position	12	11	10	9	8	7	6	5	4	3	2	1
Bits	D8	D7	D6	D5	C8	D4	D3	D2	C4	D1	C2	C1
Word												
Check bit												

d) Peripherals are connected to the computer through I/O modules. Why do we not connect the peripherals directly to the system bus?

(2 marks)

Continued...

Question 4

a) List any four characteristics of a RISC instruction set architecture.

(2 marks)

b) Directory protocols collect and maintain information about where copies of lines reside. There is a centralized controller that is part of the main memory controller, and a directory that is stored in main memory. The directory contains global state information about the contents of the various local caches. Explain how the controller is able to maintain cache coherence.

(4 marks)

Continued...

c) State and explain any two benefits of a Symmetric Multiprocessor (SMP).

(2 marks)

d) Write ARM instructions to find the 1's complement and 2's complement of a 32 bit number in memory address 0x1000 and store the result in memory addresses 0x7000 and 0x7004.

(4 marks)

End of Page.

Appendix

ARM® and Thumb®-2 Instruction Set Quick Reference Card

Key to Tables			
`Rm {, <opsh>}`	See Table **Register, optionally shifted by constant**		
`<Operand2>`	See Table **Flexible Operand 2**. Shift and rotate are only available as part of Operand2.	`<reglist>`	A comma-separated list of registers, enclosed in braces { and }.
`<fields>`	See Table **PSR fields.**	`<reglist-PC>`	As `<reglist>`, must not include the PC.
`<PSR>`	Either CPSR (Current Processor Status Register) or SPSR (Saved Processor Status Register)	`<reglist+PC>`	As `<reglist>`, including the PC.
`C*, V*`	Flag is unpredictable in Architecture v4 and earlier, unchanged in Architecture v5 and later.	`+/-`	+ or –. (+ may be omitted.)
`<Rs|sh>`	Can be Rs or an immediate shift value. The values allowed for each shift type are the same as those	§	See Table **ARM architecture versions.**
	shown in Table **Register, optionally shifted by constant.**	`<iflags>`	Interrupt flags. One or more of `a`, `i`, `f` (abort, interrupt, fast interrupt).
`x,y`	B meaning half-register [15:0], or T meaning [31:16].	`<p_mode>`	See Table **Processor Modes**
`<imm8m>`	ARM: a 32-bit constant, formed by right-rotating an 8-bit value by an even number of bits.	`SPm`	SP for the processor mode specified by `<p_mode>`
	Thumb: a 32-bit constant, formed by left-shifting an 8-bit value by any number of bits, or a bit	`<lsb>`	Least significant bit of bitfield.
	pattern of one of the forms 0xXYXYXYXY, 0x00XY00XY or 0xXY00XY00.	`<width>`	Width of bitfield. `<width>` + `<lsb>` must be <= 32.
`<prefix>`	See Table **Prefixes for Parallel instructions**	`{X}`	RsX is Rs rotated 16 bits if X present. Otherwise, RsX is Rs.
`{IA|IB|DA|DB}`	Increment After, Increment Before, Decrement After, or Decrement Before.	`{!}`	Updates base register after data transfer if ! present (pre-indexed).
	`IB` and `DA` are not available in Thumb state. If omitted, defaults to `IA`.	`{S}`	Updates condition flags if S present.
`<size>`	`B`, `SB`, `H`, or `SH`, meaning Byte, Signed Byte, Halfword, and Signed Halfword respectively.	`{T}`	User mode privilege if T present.
	`SB` and `SH` are not available in `STR` instructions.	`{R}`	Rounds result to nearest if R present, otherwise truncates result.

Operation		§	Assembler	S updates	Action	Notes
Add	Add		`ADD{S} Rd, Rn, <Operand2>`	N Z C V	Rd := Rn + Operand2	N
	with carry		`ADC{S} Rd, Rn, <Operand2>`	N Z C V	Rd := Rn + Operand2 + Carry	N
	wide	T2	`ADD Rd, Rn, #<imm12>`		Rd := Rn + imm12, imm12 range 0-4095	T, P
	saturating {doubled}	5E	`Q{D}ADD Rd, Rm, Rn`		Rd := SAT(Rm + Rn) doubled: Rd := SAT(Rm + SAT(Rn * 2))	Q
Address	Form PC-relative address		`ADR Rd, <label>`		Rd := <label>, for <label> range from current instruction see Note L	N, L
Subtract	Subtract		`SUB{S} Rd, Rn, <Operand2>`	N Z C V	Rd := Rn – Operand2	N
	with carry		`SBC{S} Rd, Rn, <Operand2>`	N Z C V	Rd := Rn – Operand2 – NOT(Carry)	N
	wide	T2	`SUB Rd, Rn, #<imm12>`	N Z C V	Rd := Rn – imm12, imm12 range 0-4095	T, P
	reverse subtract		`RSB{S} Rd, Rn, <Operand2>`	N Z C V	Rd := Operand2 – Rn	N
	reverse subtract with carry		`RSC{S} Rd, Rn, <Operand2>`	N Z C V	Rd := Operand2 – Rn – NOT(Carry)	A
	saturating {doubled}	5E	`Q{D}SUB Rd, Rm, Rn`		Rd := SAT(Rm – Rn) doubled: Rd := SAT(Rm – SAT(Rn * 2))	Q
	Exception return without stack		`SUBS PC, LR, #<imm8>`		PC = LR – imm8, CPSR = SPSR(current mode), imm8 range 0-255.	T
Parallel arithmetic	Halfword-wise addition	6	`<prefix>ADD16 Rd, Rn, Rm`		Rd[31:16] := Rn[31:16] + Rm[31:16], Rd[15:0] := Rn[15:0] + Rm[15:0]	G
	Halfword-wise subtraction	6	`<prefix>SUB16 Rd, Rn, Rm`		Rd[31:16] := Rn[31:16] – Rm[31:16], Rd[15:0] := Rn[15:0] – Rm[15:0]	G
	Byte-wise addition	6	`<prefix>ADD8 Rd, Rn, Rm`		Rd[31:24] := Rn[31:24] + Rm[31:24], Rd[23:16] := Rn[23:16] + Rm[23:16], Rd[15:8] := Rn[15:8] + Rm[15:8], Rd[7:0] := Rn[7:0] + Rm[7:0]	G
	Byte-wise subtraction	6	`<prefix>SUB8 Rd, Rn, Rm`		Rd[31:24] := Rn[31:24] – Rm[31:24], Rd[23:16] := Rn[23:16] – Rm[23:16], Rd[15:8] := Rn[15:8] – Rm[15:8], Rd[7:0] := Rn[7:0] – Rm[7:0]	G
	Halfword-wise exchange, add, subtract	6	`<prefix>ASX Rd, Rn, Rm`		Rd[31:16] := Rn[31:16] + Rm[15:0], Rd[15:0] := Rn[15:0] – Rm[31:16]	G
	Halfword-wise exchange, subtract, add	6	`<prefix>SAX Rd, Rn, Rm`		Rd[31:16] := Rn[31:16] – Rm[15:0], Rd[15:0] := Rn[15:0] + Rm[31:16]	G
	Unsigned sum of absolute differences	6	`USAD8 Rd, Rm, Rs`		Rd := Abs(Rm[31:24] – Rs[31:24]) + Abs(Rm[23:16] – Rs[23:16]) + Abs(Rm[15:8] – Rs[15:8]) + Abs(Rm[7:0] – Rs[7:0])	
	and accumulate	6	`USADA8 Rd, Rm, Rs, Rn`		Rd := Rn + Abs(Rm[31:24] – Rs[31:24]) + Abs(Rm[23:16] – Rs[23:16]) + Abs(Rm[15:8] – Rs[15:8]) + Abs(Rm[7:0] – Rs[7:0])	
Saturate	Signed saturate word, right shift	6	`SSAT Rd, #<sat>, Rm{, ASR <sh>}`		Rd := SignedSat((Rm ASR sh), sat). `<sat>` range 1-32, `<sh>` range 1-31.	Q, R
	Signed saturate word, left shift	6	`SSAT Rd, #<sat>, Rm{, LSL <sh>}`		Rd := SignedSat((Rm LSL sh), sat). `<sat>` range 1-32, `<sh>` range 0-31.	Q
	Signed saturate two halfwords	6	`SSAT16 Rd, #<sat>, Rm`		Rd[31:16] := SignedSat(Rm[31:16], sat), Rd[15:0] := SignedSat(Rm[15:0], sat). `<sat>` range 1-16.	Q
	Unsigned saturate word, right shift	6	`USAT Rd, #<sat>, Rm{, ASR <sh>}`		Rd := UnsignedSat((Rm ASR sh), sat). `<sat>` range 0-31, `<sh>` range 1-31.	Q, R
	Unsigned saturate word, left shift	6	`USAT Rd, #<sat>, Rm{, LSL <sh>}`		Rd := UnsignedSat((Rm LSL sh), sat). `<sat>` range 0-31, `<sh>` range 0-31.	Q
	Unsigned saturate two halfwords	6	`USAT16 Rd, #<sat>, Rm`		Rd[31:16] := UnsignedSat(Rm[31:16], sat), Rd[15:0] := UnsignedSat(Rm[15:0], sat). `<sat>` range 0-15.	Q

ARM and Thumb-2 Instruction Set Quick Reference Card

Operation		§	Assembler	S updates	Action	Notes
Multiply	Multiply		`MUL{S} Rd, Rm, Rs`	N Z C*	Rd := (Rm * Rs)[31:0] (If Rm is Rd, S can be used in Thumb-2)	N, S
	and accumulate		`MLA{S} Rd, Rm, Rs, Rn`	N Z C*	Rd := (Rn + (Rm * Rs))[31:0]	S
	and subtract	T2	`MLS Rd, Rm, Rs, Rn`		Rd := (Rn – (Rm * Rs))[31:0]	
	unsigned long		`UMULL{S} RdLo, RdHi, Rm, Rs`	N Z C* V*	RdHi,RdLo := unsigned(Rm * Rs)	S
	unsigned accumulate long		`UMLAL{S} RdLo, RdHi, Rm, Rs`	N Z C* V*	RdHi,RdLo := unsigned(RdHi,RdLo + Rm * Rs)	S
	unsigned double accumulate long	6	`UMAAL RdLo, RdHi, Rm, Rs`		RdHi,RdLo := unsigned(RdHi + RdLo + Rm * Rs)	
	Signed multiply long		`SMULL{S} RdLo, RdHi, Rm, Rs`	N Z C* V*	RdHi,RdLo := signed(Rm * Rs)	S
	and accumulate long		`SMLAL{S} RdLo, RdHi, Rm, Rs`	N Z C* V*	RdHi,RdLo := signed(RdHi,RdLo + Rm * Rs)	S
	16 * 16 bit	5E	`SMULxy Rd, Rm, Rs`		Rd := Rm[x] * Rs[y]	
	32 * 16 bit	5E	`SMULWy Rd, Rm, Rs`		Rd := (Rm * Rs[y])[47:16]	
	16 * 16 bit and accumulate	5E	`SMLAxy Rd, Rm, Rs, Rn`		Rd := Rn + Rm[x] * Rs[y]	Q
	32 * 16 bit and accumulate	5E	`SMLAWy Rd, Rm, Rs, Rn`		Rd := Rn + (Rm * Rs[y])[47:16]	Q
	16 * 16 bit and accumulate long	5E	`SMLALxy RdLo, RdHi, Rm, Rs`		RdHi,RdLo := RdHi,RdLo + Rm[x] * Rs[y]	
	Dual signed multiply, add	6	`SMUAD{X} Rd, Rm, Rs`		Rd := Rm[15:0] * RsX[15:0] + Rm[31:16] * RsX[31:16]	Q
	and accumulate	6	`SMLAD{X} Rd, Rm, Rs, Rn`		Rd := Rn + Rm[15:0] * RsX[15:0] + Rm[31:16] * RsX[31:16]	Q
	and accumulate long	6	`SMLALD{X} RdLo, RdHi, Rm, Rs`		RdHi,RdLo := RdHi,RdLo + Rm[15:0] * RsX[15:0] + Rm[31:16] * RsX[31:16]	
	Dual signed multiply, subtract	6	`SMUSD{X} Rd, Rm, Rs`		Rd := Rm[15:0] * RsX[15:0] – Rm[31:16] * RsX[31:16]	Q
	and accumulate	6	`SMLSD{X} Rd, Rm, Rs, Rn`		Rd := Rn + Rm[15:0] * RsX[15:0] – Rm[31:16] * RsX[31:16]	Q
	and accumulate long	6	`SMLSLD{X} RdLo, RdHi, Rm, Rs`		RdHi,RdLo := RdHi,RdLo + Rm[15:0] * RsX[15:0] – Rm[31:16] * RsX[31:16]	
	Signed top word multiply	6	`SMMUL{R} Rd, Rm, Rs`		Rd := (Rm * Rs)[63:32]	
	and accumulate	6	`SMMLA{R} Rd, Rm, Rs, Rn`		Rd := Rn + (Rm * Rs)[63:32]	
	and subtract	6	`SMMLS{R} Rd, Rm, Rs, Rn`		Rd := Rn – (Rm * Rs)[63:32]	
	with internal 40-bit accumulate	XS	`MIA Ac, Rm, Rs`		Ac := Ac + Rm * Rs	
	packed halfword	XS	`MIAPH Ac, Rm, Rs`		Ac := Ac + Rm[15:0] * Rs[15:0] + Rm[31:16] * Rs[31:16]	
	halfword	XS	`MIAxy Ac, Rm, Rs`		Ac := Ac + Rm[x] * Rs[y]	
Divide	Signed or Unsigned	RM	`<op> Rd, Rn, Rm`		Rd := Rn / Rm `<op>` is `SDIV` (signed) or `UDIV` (unsigned)	
Move data	Move		`MOV{S} Rd, <Operand2>`	N Z C	Rd := Operand2 See also Shift instructions	N
	NOT		`MVN{S} Rd, <Operand2>`	N Z C	Rd := 0xFFFFFFFF EOR Operand2	N
	top	T2	`MOVT Rd, #<imm16>`		Rd[31:16] := imm16, Rd[15:0] unaffected, imm16 range 0-65535	
	wide	T2	`MOV Rd, #<imm16>`		Rd[15:0] := imm16, Rd[31:16] = 0, imm16 range 0-65535	
	40-bit accumulator to register	XS	`MRA RdLo, RdHi, Ac`		RdLo := Ac[31:0], RdHi := Ac[39:32]	
	register to 40-bit accumulator	XS	`MAR Ac, RdLo, RdHi`		Ac[31:0] := RdLo, Ac[39:32] := RdHi	
Shift	Arithmetic shift right		`ASR{S} Rd, Rm, <Rs|sh>`	N Z C	Rd := ASR(Rm, Rs|sh) Same as `MOV{S} Rd, Rm, ASR <Rs|sh>`	N
	Logical shift left		`LSL{S} Rd, Rm, <Rs|sh>`	N Z C	Rd := LSL(Rm, Rs|sh) Same as `MOV{S} Rd, Rm, LSL <Rs|sh>`	N
	Logical shift right		`LSR{S} Rd, Rm, <Rs|sh>`	N Z C	Rd := LSR(Rm, Rs|sh) Same as `MOV{S} Rd, Rm, LSR <Rs|sh>`	N
	Rotate right		`ROR{S} Rd, Rm, <Rs|sh>`	N Z C	Rd := ROR(Rm, Rs|sh) Same as `MOV{S} Rd, Rm, ROR <Rs|sh>`	N
	Rotate right with extend		`RRX{S} Rd, Rm`	N Z C	Rd := RRX(Rm) Same as `MOV{S} Rd, Rm, RRX`	
Count leading zeros		5	`CLZ Rd, Rm`		Rd := number of leading zeros in Rm	
Compare	Compare		`CMP Rn, <Operand2>`	N Z C V	Update CPSR flags on Rn – Operand2	N
	negative		`CMN Rn, <Operand2>`	N Z C V	Update CPSR flags on Rn + Operand2	N
Logical	Test		`TST Rn, <Operand2>`	N Z C	Update CPSR flags on Rn AND Operand2	N
	Test equivalence		`TEQ Rn, <Operand2>`	N Z C	Update CPSR flags on Rn EOR Operand2	
	AND		`AND{S} Rd, Rn, <Operand2>`	N Z C	Rd := Rn AND Operand2	N
	EOR		`EOR{S} Rd, Rn, <Operand2>`	N Z C	Rd := Rn EOR Operand2	N
	ORR		`ORR{S} Rd, Rn, <Operand2>`	N Z C	Rd := Rn OR Operand2	N
	ORN	T2	`ORN{S} Rd, Rn, <Operand2>`	N Z C	Rd := Rn OR NOT Operand2	T
	Bit Clear		`BIC{S} Rd, Rn, <Operand2>`	N Z C	Rd := Rn AND NOT Operand2	N

ARM and Thumb-2 Instruction Set Quick Reference Card

Operation		§	Assembler	Action	Notes
Bit field	Bit Field Clear	T2	`BFC Rd, #<lsb>, #<width>`	Rd[(width+lsb–1):lsb] := 0, other bits of Rd unaffected	
	Bit Field Insert	T2	`BFI Rd, Rn, #<lsb>, #<width>`	Rd[(width+lsb–1):lsb] := Rn[(width-1):0], other bits of Rd unaffected	
	Signed Bit Field Extract	T2	`SBFX Rd, Rn, #<lsb>, #<width>`	Rd[(width–1):0] = Rn[(width+lsb–1):lsb], Rd[31:width] = Replicate(Rn[width+lsb–1])	
	Unsigned Bit Field Extract	T2	`UBFX Rd, Rn, #<lsb>, #<width>`	Rd[(width–1):0] = Rn[(width+lsb–1):lsb], Rd[31:width] = Replicate(0)	
Pack	Pack halfword bottom + top	6	`PKHBT Rd, Rn, Rm{, LSL #<sh>}`	Rd[15:0] := Rn[15:0], Rd[31:16] := (Rm LSL sh)[31:16], sh 0-31.	
	Pack halfword top + bottom	6	`PKHTB Rd, Rn, Rm{, ASR #<sh>}`	Rd[31:16] := Rn[31:16], Rd[15:0] := (Rm ASR sh)[15:0], sh 1-32.	
Signed extend	Halfword to word	6	`SXTH Rd, Rm{, ROR #<sh>}`	Rd[31:0] := SignExtend((Rm ROR (8 * sh))[15:0]), sh 0-3.	N
	Two bytes to halfwords	6	`SXTB16 Rd, Rm{, ROR #<sh>}`	Rd[31:16] := SignExtend((Rm ROR (8 * sh))[23:16]), Rd[15:0] := SignExtend((Rm ROR (8 * sh))[7:0]), sh 0-3.	
	Byte to word	6	`SXTB Rd, Rm{, ROR #<sh>}`	Rd[31:0] := SignExtend((Rm ROR (8 * sh))[7:0]), sh 0-3.	N
Unsigned extend	Halfword to word	6	`UXTH Rd, Rm{, ROR #<sh>}`	Rd[31:0] := ZeroExtend((Rm ROR (8 * sh))[15:0]), sh 0-3.	N
	Two bytes to halfwords	6	`UXTB16 Rd, Rm{, ROR #<sh>}`	Rd[31:16] := ZeroExtend((Rm ROR (8 * sh))[23:16]), Rd[15:0] := ZeroExtend((Rm ROR (8 * sh))[7:0]), sh 0-3.	
	Byte to word	6	`UXTB Rd, Rm{, ROR #<sh>}`	Rd[31:0] := ZeroExtend((Rm ROR (8 * sh))[7:0]), sh 0-3.	N
Signed extend with add	Halfword to word, add	6	`SXTAH Rd, Rn, Rm{, ROR #<sh>}`	Rd[31:0] := Rn[31:0] + SignExtend((Rm ROR (8 * sh))[15:0]), sh 0-3.	
	Two bytes to halfwords, add	6	`SXTAB16 Rd, Rn, Rm{, ROR #<sh>}`	Rd[31:16] := Rn[31:16] + SignExtend((Rm ROR (8 * sh))[23:16]), Rd[15:0] := Rn[15:0] + SignExtend((Rm ROR (8 * sh))[7:0]), sh 0-3.	
	Byte to word, add	6	`SXTAB Rd, Rn, Rm{, ROR #<sh>}`	Rd[31:0] := Rn[31:0] + SignExtend((Rm ROR (8 * sh))[7:0]), sh 0-3.	
Unsigned extend with add	Halfword to word, add	6	`UXTAH Rd, Rn, Rm{, ROR #<sh>}`	Rd[31:0] := Rn[31:0] + ZeroExtend((Rm ROR (8 * sh))[15:0]), sh 0-3.	
	Two bytes to halfwords, add	6	`UXTAB16 Rd, Rn, Rm{, ROR #<sh>}`	Rd[31:16] := Rn[31:16] + ZeroExtend((Rm ROR (8 * sh))[23:16]), Rd[15:0] := Rn[15:0] + ZeroExtend((Rm ROR (8 * sh))[7:0]), sh 0-3.	
	Byte to word, add	6	`UXTAB Rd, Rn, Rm{, ROR #<sh>}`	Rd[31:0] := Rn[31:0] + ZeroExtend((Rm ROR (8 * sh))[7:0]), sh 0-3.	
Reverse	Bits in word	T2	`RBIT Rd, Rm`	For (i = 0; i < 32; i++) : Rd[i] = Rm[31– i]	
	Bytes in word	6	`REV Rd, Rm`	Rd[31:24] := Rm[7:0], Rd[23:16] := Rm[15:8], Rd[15:8] := Rm[23:16], Rd[7:0] := Rm[31:24]	N
	Bytes in both halfwords	6	`REV16 Rd, Rm`	Rd[15:8] := Rm[7:0], Rd[7:0] := Rm[15:8], Rd[31:24] := Rm[23:16], Rd[23:16] := Rm[31:24]	N
	Bytes in low halfword, sign extend	6	`REVSH Rd, Rm`	Rd[15:8] := Rm[7:0], Rd[7:0] := Rm[15:8], Rd[31:16] := Rm[7] * &FFFF	N
Select	Select bytes	6	`SEL Rd, Rn, Rm`	Rd[7:0] := Rn[7:0] if GE[0] = 1, else Rd[7:0] := Rm[7:0] Bits[15:8], [23:16], [31:24] selected similarly by GE[1], GE[2], GE[3]	
If-Then	If-Then	T2	`IT{pattern} {cond}`	Makes up to four following instructions conditional, according to pattern. pattern is a string of up to three letters. Each letter can be T (Then) or E (Else). The first instruction after IT has condition cond. The following instructions have condition cond if the corresponding letter is T, or the inverse of cond if the corresponding letter is E. See Table **Condition Field** for available condition codes.	T U
Branch	Branch		`B <label>`	PC := label. label is this instruction ±32MB (T2: ±16MB, T: –252 - +256B)	N, B
	with link		`BL <label>`	LR := address of next instruction, PC := label. label is this instruction ±32MB (T2: ±16MB).	
	and exchange	4T	`BX Rm`	PC := Rm. Target is Thumb if Rm[0] is 1, ARM if Rm[0] is 0.	N
	with link and exchange (1)	5T	`BLX <label>`	LR := address of next instruction, PC := label, Change instruction set. label is this instruction ±32MB (T2: ±16MB).	C
	with link and exchange (2)	5	`BLX Rm`	LR := address of next instruction, PC := Rm[31:1], Change to Thumb if Rm[0] is 1, to ARM if Rm[0] is 0.	N
	and change to Jazelle state	5J	`BXJ Rm`	Change to Jazelle state if available	
	Compare, branch if (non) zero	T2	`CB(N)Z Rn,<label>`	If Rn {== or !=} 0 then PC := label. label is (this instruction + 4-130).	N T U
	Table Branch Byte	T2	`TBB [Rn, Rm]`	PC = PC + ZeroExtend(Memory(Rn + Rm, 1) << 1). Branch range 4-512. Rn can be PC.	T U
	Table Branch Halfword	T2	`TBH [Rn, Rm, LSL #1]`	PC = PC + ZeroExtend(Memory(Rn + Rm << 1, 2) << 1). Branch range 4-131072. Rn can be PC.	T U
Move to or from PSR	PSR to register		`MRS Rd, <PSR>`	Rd := PSR	
	register to PSR		`MSR <PSR>_<fields>, Rm`	PSR := Rm (selected bytes only)	
	immediate to PSR		`MSR <PSR>_<fields>, #<imm8m>`	PSR := immed_8r (selected bytes only)	
Processor state change	Change processor state	6	`CPSID <iflags> {, #<p_mode>}`	Disable specified interrupts, optional change mode.	U, N
		6	`CPSIE <iflags> {, #<p_mode>}`	Enable specified interrupts, optional change mode.	U, N
	Change processor mode	6	`CPS #<p_mode>`		U
	Set endianness	6	`SETEND <endianness>`	Sets endianness for loads and saves. `<endianness>` can be `BE` (Big Endian) or `LE` (Little Endian).	U, N

ARM Instruction Set Quick Reference Card

Single data item loads and stores		§	Assembler	Action if `<op>` is LDR	Action if `<op>` is STR	Notes
Load or store word, byte or halfword	Immediate offset		`<op>{size}{T} Rd, [Rn {, #<offset>}]{!}`	Rd := [address, size]	[address, size] := Rd	1, N
	Post-indexed, immediate		`<op>{size}{T} Rd, [Rn], #<offset>`	Rd := [address, size]	[address, size] := Rd	2
	Register offset		`<op>{size} Rd, [Rn, +/-Rm {, <opsh>}]{!}`	Rd := [address, size]	[address, size] := Rd	3, N
	Post-indexed, register		`<op>{size}{T} Rd, [Rn], +/-Rm {, <opsh>}`	Rd := [address, size]	[address, size] := Rd	4
	PC-relative		`<op>{size} Rd, <label>`	Rd := [label, size]	Not available	5, N
Load or store doubleword	Immediate offset	5E	`<op>D Rd1, Rd2, [Rn {, #<offset>}]{!}`	Rd1 := [address], Rd2 := [address + 4]	[address] := Rd1, [address + 4] := Rd2	6, 9
	Post-indexed, immediate	5E	`<op>D Rd1, Rd2, [Rn], #<offset>`	Rd1 := [address], Rd2 := [address + 4]	[address] := Rd1, [address + 4] := Rd2	6, 9
	Register offset	5E	`<op>D Rd1, Rd2, [Rn, +/-Rm {, <opsh>}]{!}`	Rd1 := [address], Rd2 := [address + 4]	[address] := Rd1, [address + 4] := Rd2	7, 9
	Post-indexed, register	5E	`<op>D Rd1, Rd2, [Rn], +/-Rm {, <opsh>}`	Rd1 := [address], Rd2 := [address + 4]	[address] := Rd1, [address + 4] := Rd2	7, 9
	PC-relative	5E	`<op>D Rd1, Rd2, <label>`	Rd1 := [label], Rd2 := [label + 4]	Not available	8, 9

Preload data or instruction		§ (PLD)	§ (PLI)	Assembler	Action if `<op>` is PLD	Action if `<op>` is PLI	Notes
	Immediate offset	5E	7	`<op> [Rn {, #<offset>}]`	Preload [address, 32] (data)	Preload [address, 32] (instruction)	1, C
	Register offset	5E	7	`<op> [Rn, +/-Rm {, <opsh>}]`	Preload [address, 32] (data)	Preload [address, 32] (instruction)	3, C
	PC-relative	5E	7	`<op> <label>`	Preload [label, 32] (data)	Preload [label, 32] (instruction)	5, C

Other memory operations		§	Assembler	Action	Notes
Load multiple	Block data load		`LDM{IA|IB|DA|DB} Rn{!}, <reglist-PC>`	Load list of registers from [Rn]	N, I
	return (and exchange)		`LDM{IA|IB|DA|DB} Rn{!}, <reglist+PC>`	Load registers, PC := [address][31:1] (§ 5T: Change to Thumb if [address][0] is 1)	I
	and restore CPSR		`LDM{IA|IB|DA|DB} Rn{!}, <reglist+PC>^`	Load registers, branch (§ 5T: and exchange), CPSR := SPSR. Exception modes only.	I
	User mode registers		`LDM{IA|IB|DA|DB} Rn, <reglist-PC>^`	Load list of User mode registers from [Rn]. Privileged modes only.	I
Pop			`POP <reglist>`	Canonical form of `LDM SP!, <reglist>`	N
Load exclusive	Semaphore operation	6	`LDREX Rd, [Rn]`	Rd := [Rn], tag address as exclusive access. Outstanding tag set if not shared address. Rd, Rn not PC.	
	Halfword or Byte	6K	`LDREX{H|B} Rd, [Rn]`	Rd[15:0] := [Rn] or Rd[7:0] := [Rn], tag address as exclusive access. Outstanding tag set if not shared address. Rd, Rn not PC.	
	Doubleword	6K	`LDREXD Rd1, Rd2, [Rn]`	Rd1 := [Rn], Rd2 := [Rn+4], tag addresses as exclusive access Outstanding tags set if not shared addresses. Rd1, Rd2, Rn not PC.	9
Store multiple	Push, or Block data store		`STM{IA|IB|DA|DB} Rn{!}, <reglist>`	Store list of registers to [Rn]	N, I
	User mode registers		`STM{IA|IB|DA|DB} Rn{!}, <reglist>^`	Store list of User mode registers to [Rn]. Privileged modes only.	I
Push			`PUSH <reglist>`	Canonical form of `STMDB SP!, <reglist>`	N
Store exclusive	Semaphore operation	6	`STREX Rd, Rm, [Rn]`	If allowed, [Rn] := Rm, clear exclusive tag, Rd := 0. Else Rd := 1. Rd, Rm, Rn not PC.	
	Halfword or Byte	6K	`STREX{H|B} Rd, Rm, [Rn]`	If allowed, [Rn] := Rm[15:0] or [Rn] := Rm[7:0], clear exclusive tag, Rd := 0. Else Rd := 1 Rd, Rm, Rn not PC.	
	Doubleword	6K	`STREXD Rd, Rm1, Rm2, [Rn]`	If allowed, [Rn] := Rm1, [Rn+4] := Rm2, clear exclusive tags, Rd := 0. Else Rd := 1 Rd, Rm1, Rm2, Rn not PC.	9
Clear exclusive		6K	`CLREX`	Clear local processor exclusive tag	C

Notes: availability and range of options for Load, Store, and Preload operations

Note	ARM Word, B, D	ARM SB, H, SH	ARM T, BT	Thumb-2 Word, B, SB, H, SH, D	Thumb-2 T, BT, SBT, HT, SHT
1	offset: -4095 to +4095	offset: -255 to +255	Not available	offset: -255 to +255 if writeback, -255 to +4095 otherwise	offset: 0 to +255, writeback not allowed
2	offset: -4095 to +4095	offset: -255 to +255	offset: -4095 to +4095	offset: -255 to +255	Not available
3	Full range of `{, <opsh>}`	`{, <opsh>}` not allowed	Not available	`<opsh>` restricted to `LSL #<sh>`, `<sh>` range 0 to 3	Not available
4	Full range of `{, <opsh>}`	`{, <opsh>}` not allowed	Full range of `{, <opsh>}`	Not available	Not available
5	label within +/- 4092 of current instruction	Not available	Not available	label within +/- 4092 of current instruction	Not available
6	offset: –255 to +255	-	-	offset: –1020 to +1020, must be multiple of 4.	-
7	`{, <opsh>}` not allowed	-	-	Not available	-
8	label within +/- 252 of current instruction	-	-	Not available	-
9	Rd1 even, and not r14, Rd2 == Rd1 + 1.	-	-	Rd1 != PC, Rd2 != PC	-

ARM Instruction Set Quick Reference Card

Coprocessor operations	§	Assembler		Action	Notes
Data operations		`CDP{2} <copr>, <op1>, CRd, CRn, CRm{, <op2>}`		Coprocessor defined	C2
Move to ARM register from coprocessor		`MRC{2} <copr>, <op1>, Rd, CRn, CRm{, <op2>}`		Coprocessor defined	C2
Two ARM register move	5E	`MRRC <copr>, <op1>, Rd, Rn, CRm`		Coprocessor defined	
Alternative two ARM register move	6	`MRRC2 <copr>, <op1>, Rd, Rn, CRm`		Coprocessor defined	C
Move to coproc from ARM reg		`MCR{2} <copr>, <op1>, Rd, CRn, CRm{, <op2>}`		Coprocessor defined	C2
Two ARM register move	5E	`MCRR <copr>, <op1>, Rd, Rn, CRm`		Coprocessor defined	
Alternative two ARM register move	6	`MCRR2 <copr>, <op1>, Rd, Rn, CRm`		Coprocessor defined	C
Loads and stores, pre-indexed		`<op>{2} <copr>, CRd, [Rn, #+/-<offset8*4>]{!}`	op: LDC or STC. offset: multiple of 4 in range 0 to 1020.	Coprocessor defined	C2
Loads and stores, zero offset		`<op>{2} <copr>, CRd, [Rn] {, 8-bit copro. option}`	op: LDC or STC.	Coprocessor defined	C2
Loads and stores, post-indexed		`<op>{2} <copr>, CRd, [Rn], #+/-<offset8*4>`	op: LDC or STC. offset: multiple of 4 in range 0 to 1020.	Coprocessor defined	C2

Miscellaneous operations		§	Assembler	Action	Notes
Swap word			`SWP Rd, Rm, [Rn]`	temp := [Rn], [Rn] := Rm, Rd := temp.	D
Swap byte			`SWPB Rd, Rm, [Rn]`	temp := ZeroExtend([Rn][7:0]), [Rn][7:0] := Rm[7:0], Rd := temp	D
Store return state		6	`SRS{IA|IB|DA|DB} SP{!}, #<p_mode>`	[SPm] := LR, [SPm + 4] := CPSR	C, I
Return from exception		6	`RFE{IA|IB|DA|DB} Rn{!}`	PC := [Rn], CPSR := [Rn + 4]	C, I
Breakpoint		5	`BKPT <imm16>`	Prefetch abort or enter debug state. 16-bit bitfield encoded in instruction.	C, N
Secure Monitor Call		Z	`SMC <imm16>`	Secure Monitor Call exception. 16-bit bitfield encoded in instruction. Formerly SMI.	
Supervisor Call			`SVC <imm24>`	Supervisor Call exception. 24-bit bitfield encoded in instruction. Formerly SWI.	N
No operation		6	`NOP`	None, might not even consume any time.	N
Hints	Debug Hint	7	`DBG`	Provide hint to debug and related systems.	
	Data Memory Barrier	7	`DMB`	Ensure the order of observation of memory accesses.	C
	Data Synchronization Barrier	7	`DSB`	Ensure the completion of memory accesses.	C
	Instruction Synchronization Barrier	7	`ISB`	Flush processor pipeline and branch prediction logic.	C
	Set event	T2	`SEV`	Signal event in multiprocessor system. NOP if not implemented.	N
	Wait for event	T2	`WFE`	Wait for event, IRQ, FIQ, Imprecise abort, or Debug entry request. NOP if not implemented.	N
	Wait for interrupt	T2	`WFI`	Wait for IRQ, FIQ, Imprecise abort, or Debug entry request. NOP if not implemented.	N
	Yield	T2	`YIELD`	Yield control to alternative thread. NOP if not implemented.	N

Notes			
A	Not available in Thumb state.	**N**	Some or all forms of this instruction are 16-bit (Narrow) instructions in Thumb-2 code. For details see the *Thumb 16-bit Instruction Set (UAL) Quick Reference Card.*
B	Can be conditional in Thumb state without having to be in an IT block.		
C	Condition codes are not allowed in ARM state.	**P**	Rn can be the PC in Thumb state in this instruction.
C2	The optional 2 is available from ARMv5. It provides an alternative operation. Condition codes are not allowed for the alternative form in ARM state.	**Q**	Sets the Q flag if saturation (addition or substraction) or overflow (multiplication) occurs. Read and reset the Q flag using MRS and MSR.
D	Deprecated. Use LDREX and STREX instead.	**R**	`<sh>` range is 1-32 in the ARM instruction.
G	Updates the four GE flags in the CPSR based on the results of the individual operations.	**S**	The S modifier is not available in the Thumb-2 instruction.
I	IA is the default, and is normally omitted.	**T**	Not available in ARM state.
L	ARM: <imm8m>. 16-bit Thumb: multiple of 4 in range 0-1020. 32-bit Thumb: 0-4095.	**U**	Not allowed in an IT block. Condition codes not allowed in either ARM or Thumb state.

ARM Instruction Set Quick Reference Card

ARM architecture versions	
n	ARM architecture version *n* and above
*n*T, *n*J	T or J variants of ARM architecture version *n* and above
5E	ARM v5E, and 6 and above
T2	All Thumb-2 versions of ARM v6 and above
6K	ARMv6K and above for ARM instructions, ARMv7 for Thumb
Z	All Security extension versions of ARMv6 and above
RM	ARMv7-R and ARMv7-M only
XS	XScale coprocessor instruction

Flexible Operand 2	
Immediate value	`#<imm8m>`
Register, optionally shifted by constant (see below)	`Rm {, <opsh>}`
Register, logical shift left by register	`Rm, LSL Rs`
Register, logical shift right by register	`Rm, LSR Rs`
Register, arithmetic shift right by register	`Rm, ASR Rs`
Register, rotate right by register	`Rm, ROR Rs`

Register, optionally shifted by constant		
(No shift)	`Rm`	Same as `Rm, LSL #0`
Logical shift left	`Rm, LSL #<shift>`	Allowed shifts 0-31
Logical shift right	`Rm, LSR #<shift>`	Allowed shifts 1-32
Arithmetic shift right	`Rm, ASR #<shift>`	Allowed shifts 1-32
Rotate right	`Rm, ROR #<shift>`	Allowed shifts 1-31
Rotate right with extend	`Rm, RRX`	

PSR fields	(use at least one suffix)	
Suffix	**Meaning**	
`c`	Control field mask byte	PSR[7:0]
`f`	Flags field mask byte	PSR[31:24]
`s`	Status field mask byte	PSR[23:16]
`x`	Extension field mask byte	PSR[15:8]

Condition Field		
Mnemonic	**Description**	**Description (VFP)**
`EQ`	Equal	Equal
`NE`	Not equal	Not equal, or unordered
`CS / HS`	Carry Set / Unsigned higher or same	Greater than or equal, or unordered
`CC / LO`	Carry Clear / Unsigned lower	Less than
`MI`	Negative	Less than
`PL`	Positive or zero	Greater than or equal, or unordered
`VS`	Overflow	Unordered (at least one NaN operand)
`VC`	No overflow	Not unordered
`HI`	Unsigned higher	Greater than, or unordered
`LS`	Unsigned lower or same	Less than or equal
`GE`	Signed greater than or equal	Greater than or equal
`LT`	Signed less than	Less than, or unordered
`GT`	Signed greater than	Greater than
`LE`	Signed less than or equal	Less than or equal, or unordered
`AL`	Always (normally omitted)	Always (normally omitted)

All ARM instructions (except those with Note C or Note U) can have any one of these condition codes after the instruction mnemonic (that is, before the first space in the instruction as shown on this card). This condition is encoded in the instruction.

All Thumb-2 instructions (except those with Note U) can have any one of these condition codes after the instruction mnemonic. This condition is encoded in a preceding IT instruction (except in the case of conditional Branch instructions). Condition codes in instructions must match those in the preceding IT instruction.

On processors without Thumb-2, the only Thumb instruction that can have a condition code is `B <label>`.

Processor Modes	
16	User
17	FIQ Fast Interrupt
18	IRQ Interrupt
19	Supervisor
23	Abort
27	Undefined
31	System

Prefixes for Parallel Instructions	
`S`	Signed arithmetic modulo 2^8 or 2^{16}, sets CPSR GE bits
`Q`	Signed saturating arithmetic
`SH`	Signed arithmetic, halving results
`U`	Unsigned arithmetic modulo 2^8 or 2^{16}, sets CPSR GE bits
`UQ`	Unsigned saturating arithmetic
`UH`	Unsigned arithmetic, halving results

Document Number

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Change Log

Issue	Date	Change	Issue	Date	Change
A	June 1995	First Release	B	Sept 1996	Second Release
C	Nov 1998	Third Release	D	Oct 1999	Fourth Release
E	Oct 2000	Fifth Release	F	Sept 2001	Sixth Release
G	Jan 2003	Seventh Release	H	Oct 2003	Eighth Release
I	Dec 2004	Ninth Release	J	May 2005	RVCT 2.2 SP1
K	March 2006	RVCT 3.0	L	March 2007	RVCT 3.1